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TECHNICAL NOTE

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EFFECTS OF VARIOUS AGING HEAT TREATMENTS AND SOLUTION-ANNEALING AND AGING HEAT TREATMENTS ON TENSILE, CREEP, AND STRESS-RUPTURE STRENGTHS OF INCONEL X SHEET TO TEMPERATURES OF 1,400° F

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TECHNICAL NOTE D-374

EFFECTS OF VARIOUS AGING HEAT TREATMENTS AND SOLUTION-ANNEALING AND AGING HEAT TREATMENTS ON TENSILE, CREEP, AND STRESS-RUPTURE STRENGTHS OF INCONEL X SHEET TO TEMPERATURES OF $1,400^{\circ}$ F

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SUMMARY

The tensile strength, the 0.2-percent creep strength in 5 and 10 hours, the 10- and 100-hour stress-rupture strength, and the minimum creep rate of Inconel X sheet at $1,000^{\circ}$, $1,200^{\circ}$, and $1,400^{\circ}$ F were determined for three aging and three solution-annealing and aging treatments. The best tensile strengths were provided by the aging treatments. The aging treatments also had the highest 0.2-percent creep strength in 5 and 10 hours and 10-hour stress-rupture strength at $1,000^{\circ}$, $1,200^{\circ}$, and $1,400^{\circ}$ F. The solution-annealing and aging heat treatments had the best 100-hour stress-rupture strength at $1,200^{\circ}$ F. At $1,400^{\circ}$ F test temperature, the aging treatment at $1,400^{\circ}$ F for 1 hour had the superior 100-hour stress-rupture strength. The lowest minimum creep rates at test temperatures of $1,000^{\circ}$ and $1,200^{\circ}$ F were obtained by aging at $1,300^{\circ}$ F for 20 hours and the 2-hour solution-annealing and aging treatments, respectively. At $1,400^{\circ}$ F the minimum creep rates were nearly the same for all heat treatments.

INTRODUCTION

Heat-resistant structural materials, such as Inconel X sheet, presently are being used for very high-speed aircraft and missile structural applications. Although considerable data are available on the elevated-temperature properties and on the effects of various thermal treatments for Inconel X bar material (for example, refs. 1 and 2), there is comparatively little such information on this alloy in sheet form. Some scattered information on the effect of heat treatments on Inconel X sheet may be found in references 3 to 11. Some recent information on bar and sheet material is given in reference 12.

There are a number of thermal treatments - solution-annealing and aging treatments or aging treatments - which have been used to develop the optimum properties of this alloy at various temperature levels. The suitability or limitations of some of these heat treatments have not been clearly defined, except for long-time creep applications.

Presented herein are the results of an investigation to determine the effects of three solution-annealing and aging heat treatments and three aging heat treatments on the tensile and creep properties of Inconel X sheet. Room-temperature tension tests, short-time elevated-temperature tension tests, and creep and stress-rupture tests up to 100 hours of rupture life were made at $1,000^\circ$, $1,200^\circ$, and $1,400^\circ$ F. The results presented in graphical and tabular form show which heat treatments give the optimum tensile or creep properties at the different test temperatures.

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MATERIAL AND PROCEDURE

Material

The Inconel X sheet used in this investigation was supplied in the mill-annealed condition by The International Nickel Co., Inc. The nominal and actual chemical compositions of this 0.050-inch-thick sheet are given in table 1, and the mill-annealing treatment is noted in table 2.

Specimens

The tensile and creep specimens were cut from the sheet with the longitudinal axis of the specimens taken parallel to the rolling direction. The same kind of specimen was used in the tensile and creep tests. The specimen dimensions are shown in figure 1. All specimens were cut to finished size before heat treatment.

Heat Treatments

Six different heat treatments were used and are summarized in table 2. In three of them, the material was solution annealed and aged and in the other three, the material was given various aging treatments. The solution-annealing and aging treatments consisted of heating to $2,100^\circ \pm 15^\circ$ F for 1/2, 2, or 4 hours, and then aging at $1,550^\circ \pm 15^\circ$ F for 24 hours and $1,300^\circ \pm 10^\circ$ F for 20 hours. The aging treatments consisted of heating to $1,300^\circ \pm 10^\circ$ F for 20 hours, $1,400^\circ \pm 10^\circ$ F for 1 hour, and $1,400^\circ \pm 10^\circ$ for 4 hours. All specimens were heat treated in air in an electric furnace and were air cooled after each solution-annealing and aging treatment.

Test Procedure

The elevated-temperature tensile stress-strain tests were run at a strain rate of 0.002 per minute throughout the tests. The specimen was loaded after 1/2-hour exposure to the test temperature. The equipment and procedure were the same as described in reference 5. Some additional tests were run at room temperature with 10-inch tensile specimens using Tuckerman optical strain gages to determine Young's modulus.

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The creep tests were run in lever-type 12,000-pound-capacity creep-testing machines. As in the tension tests, the load was applied after 1/2-hour exposure to the test temperature. Strains were measured over a 1-inch gage length with two linear differential transformer gages in the same manner as in the tension tests. (See fig. 2 of ref. 5.) Temperatures were controlled within $\pm 5^{\circ}$ F in both the tension and creep tests.

RESULTS AND DISCUSSION

Tensile Tests

The room- and elevated-temperature tensile stress-strain test results are presented in figures 2 to 6. Tables 3 to 5 give the individual test results for the tensile yield strength, tensile strength, Young's modulus, and elongation in 2 inches.

Representative stress-strain curves for the three aging thermal treatments are given in figure 2 for test temperatures of 80°, 1,000°, 1,200°, and 1,400° F. The aging treatment of 1,300° F for 20 hours gives yield strengths at room and elevated temperatures as high as or higher than any of the other aging treatments. A shorter aging time, 1,400° for 4 hours resulted in a slight reduction in the tensile yield strength. The lowest yield strength in each case resulted from the heat treatment at 1,400° F for 1 hour.

Representative stress-strain curves for the three solution-annealing and aging heat treatments are shown in figure 3. At each temperature the 0.2-percent-offset yield stresses for the 1/2-hour solution annealing and aging are equal to or higher than the 2- or 4-hour solution annealing and aging. Except at 1,400° F, the lowest yield strength at each temperature was obtained for the 4-hour solution annealing and aging. The 0.2-percent-offset yield strength is indicated by the tick mark on each curve.

The tensile strength, yield strength, and elongation in 2 inches for the six heat treatments and the as-received material are compared in figure 4 for test temperatures of 80°, 1,000°, 1,200°, and 1,400° F. It is evident from this figure that the aging treatment of 1,300° F for 20 hours produced tensile strengths and yield strengths at all aforementioned temperatures which are about the same or higher than any of the other thermal treatments. At 1,400° F the tensile strength and yield strength developed by aging at 1,300° F for 20 hours and at 1,400° F for 4 hours are nearly the same. The tensile and yield strengths for the as-received material (mill-annealed condition) are substantially less than those obtained for the various heat treatments at all test temperatures except at 1,400° F.

The average values of the elongation for each heat treatment at test temperatures of 1,200° and 1,400° F vary from about 2 to 6 percent and are only a small fraction of the elongation at room temperature which ranges from about 14 to 33 percent (fig. 4). The greatest elongation at 1,200° and 1,400° F (5 and 6 percent, respectively) was obtained with the aging treatment at 1,400° F for 1 hour and the solution-annealing and aging treatment at 2,100° F for 4 hours. The elongation for the as-received material was much greater at each temperature than it was for the heat-treated material except at 1,400° F. The highest elongation at room temperature for the heat-treated material was obtained with the aging treatment at 1,400° F for 1 hour. Because of the low ductility of this alloy at 1,200° and 1,400° F it may be advisable to stress-relieve the material after forming and before aging in order to minimize cracking on hardening, if high fabrication stresses are involved. (See ref. 11.)

Additional comparisons of the tensile and yield strengths for four heat treatments are shown in figure 5. The curves illustrate the upper and lower limits of tensile and yield strengths obtained from the aging and the solution-annealing and aging heat treatments. The aging treatment at 1,300° F for 20 hours gave the best tensile strength and yield strength over the entire temperature range. (Almost the same strengths were obtained with the heat treatment at 1,400° F for 4 hours.) The lowest tensile strength obtained with the least favorable aging treatment (1,400° F for 1 hour) was about as high as or higher than the highest tensile strength obtained with the best solution-annealing and aging treatment (2,100° F for 1/2 hour). The superiority of the aging treatments is even more noticeable when comparisons are based on yield strengths (fig. 5(a)).

The variation of Young's modulus with temperature is shown in figure 6. The test points show the results obtained for the material in the as-received condition, after solution-annealing and aging treatments, and after the aging treatments. The test points are average values for each case. Since no individual trends are evident, a single curve holds adequately for all various treatments. At 1,400° F, the modulus is about two-thirds of its room-temperature value.

Creep and Stress-Rupture Tests

The minimum creep rate, the creep strength for 0.2-percent creep strain in 5 and 10 hours, and the 10- and 100-hour stress-rupture strengths at 1,000°, 1,200°, and 1,400° F are presented in tables 6 and 7 and illustrated in figures 7, 8, and 9. No attempt was made to obtain data for all the various heat treatments at temperatures other than 1,200° F because of the number of tests involved.

The lowest minimum creep rate at 1,000° F was obtained with the heat treatment at 1,300° F for 20 hours as shown in figure 7. At 1,200° F the lowest minimum creep rate resulted from 1/2-hour solution annealing and aging. The creep rates at 1,400° F were about the same for the heat treatments shown. The minimum creep rates are listed in table 6.

The creep strength for 0.2-percent creep strain in 5 and 10 hours for all six heat treatments is illustrated by the bar graph shown in figure 8. The highest strength at 1,000° F for 0.2-percent creep in 5 and 10 hours was obtained with the 20-hour aging heat treatment at 1,300° F. At 1,200° F, the creep strengths in 5 or 10 hours were about the same for all heat treatments, except the slightly lower strengths resulting from aging at 1,400° F for 1 hour. At 1,400° F, the highest creep strength was obtained by aging at 1,300° F for 20 hours; creep strengths for the other heat treatments (table 7) were slightly lower.

Stress-rupture strengths for 10 and 100 hours are illustrated in the same manner in figure 9. The best stress-rupture properties for 10 hours at 1,000° F were obtained with the aging treatment at 1,300° F for 20 hours. At the test temperature of 1,200° F, the aging treatment at 1,400° F for 4 hours gave the highest rupture strength in 10 hours. At 1,400° F, however, the difference between the results obtained for rupture in 10 hours for the various heat treatments was slight.

For a stress-rupture life of 100 hours at 1,000° F (fig. 9), the aging treatment at 1,300° F for 20 hours developed the highest strength. At 1,200° F the three solution-annealing and aging heat treatments produced about the same strengths; these strengths were somewhat better than those obtained with the aging treatments. This is the only case in which the solution annealing and aging heat treatments proved advantageous over the aging heat treatments. The aging treatment at 1,400° F for 1 hour was superior at 1,400° F with regard to the 100-hour stress-rupture strength.

Hardness Tests

Hardness measurements shown in table 2 are average room-temperature values for all the specimens for each heat treatment. A comparison of the hardness results of table 2 with the tensile strengths at room temperature in tables 3 to 5 indicates that the hardness values are commensurate with the tensile strengths; that is, the hardness increases as the strength increases. The aging treatment of 1,300° F for 20 hours produces the greatest tensile strength as well as the highest hardness at room temperature.

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Photomicrographic Results

The photomicrographs in figures 10(a), 10(b), and 10(c) illustrate representative microstructural conditions resulting from each system of heat treatment. Figure 10(a) shows that as the solution annealing time increases from 1/2 to 4 hours some grain coarsening occurs and there is an appearance of numerous annealing twins. More twinning is also evident for longer times for low-temperature aging (fig. 10(b)). These latter photomicrographs show a uniform grain size of the order of ASTM 5 or 6; the grains for the solution-annealed material in figure 10(a) are larger. A photomicrograph of the material in the as-received mill-annealed condition is shown in figure 10(c).

Some X-ray diffraction results of the as-received material, the specimens solution annealed at 2,100° F for 1/2 hour and aged, and the specimens aged at 1,300° F for 20 hours showed no noticable indications of preferred grain orientations in the plane of the sheet. No attempt was made to correlate the grain size and microstructure with differences in tensile or creep properties.

CONCLUDING REMARKS

The results of an investigation of the effects of three solution-annealing and aging heat treatments and three aging heat treatments showed that the best tensile yield strength and tensile ultimate strength from 80° F to 1,400° F was obtained with the aging treatment of 1,300° F for 20 hours. Only a small loss in strength is experienced when the shorter heat treatment at 1,400° F for 4 hours is used. At 1,400° F Young's modulus is about two-thirds of the room-temperature value. The elongation in 2 inches at 1,200° and 1,400° F, however, was unduly low (2 to 6 percent) for all the various heat treatments. If high fabrication stresses are present before heat treatment, some stress-relieving treatment may be advisable in order to avoid the possibility of cracking due to aging.

The aging heat treatments developed the lowest minimum creep rates at $1,000^{\circ}$ F whereas the heat treatment consisting of 1/2-hour solution annealing and aging had this distinction at $1,200^{\circ}$ F. At $1,400^{\circ}$ F little difference in the creep rates resulted from the heat treatments.

The highest strength for 0.2-percent creep strain in 5 and 10 hours and for 10- and 100-hour stress rupture at $1,000^{\circ}$ F was obtained after aging at $1,300^{\circ}$ F for 20 hours. Approximately the same strength resulted from either the aging or solution annealing and aging treatments at $1,200^{\circ}$ F for 0.2-percent creep in 5 hours and 10 hours except for the lower creep strength obtained with specimens aged at $1,400^{\circ}$ F for 1 hour. Only in the stress-rupture tests for 100 hours at $1,200^{\circ}$ F were the solution-annealing and aging treatments superior to the shorter-time aging treatments.

There appears to be no need for using the relatively long high-temperature solution-annealing and aging treatments for short-time tensile stress-strain applications or for applications in which 0.2-percent creep strain or stress-rupture in 5 or 10 hours is involved. Strengths equal to or better than those obtained with the solution-annealing and aging treatments can be obtained from relatively short low-temperature aging treatments.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., February 1, 1960.

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TABLE 1.- CHEMICAL COMPOSITION OF INCONEL X SHEET

OF 0.050-INCH THICKNESS

[All values are in percent by weight]

Element	Nominal composition (a)	Actual composition (b)
Nickel	70 (minimum)	72.77
Chromium	14 to 16	14.98
Iron	5 to 9	6.82
Titanium	2.25 to 2.75	2.45
Columbium	.7 to 1.2	.96
Aluminum	.4 to 1.0	.76
Silicon	.5 (maximum)	.37
Manganese	.3 to 1.0	.74
Copper	.2 (maximum)	.06
Carbon	.08 (maximum)	.06
Sulfur	.01 (maximum)	.007

[a]From reference 1.

[b]Analysis supplied by manufacturer for Heat No. 2814-X.

TABLE 2.- HEAT TREATMENTS AND HARDNESS MEASUREMENTS

FOR INCONEL X SHEET

Condition	Solution treatment			Aging treatment			Hardness at room temperature, Rockwell 15N scale
	Time, hr	Temperature, °F	Cooling	Time, hr	Temperature, °F	Cooling	
Aged				20	1,300	Air	78.6
Aged				4	1,400	Air	78.1
Aged				1	1,400	Air	76.9
Solution annealed and aged	1/2	2,100	Air	24	1,550	Air	76.6
				20	1,300	Air	
Solution annealed and aged	2	2,100	Air	24	1,550	Air	76.2
				20	1,300	Air	
Solution annealed and aged	4	2,100	Air	24	1,550	Air	75.4
				20	1,300	Air	
Mill annealed (as received)	1/4 to 1/2	1,900 to 2,000	Air				63.4

TABLE 3.- TENSILE PROPERTIES OF AGED INCONEL X SHEET

(a) 1,300° F for 20 hours (air cooled)

Temperature, °F	Yield strength, ksi	Tensile strength, ksi	Young's modulus, psi	Elongation in 2 in., percent
80	121	177	[a]30.3×10^6	28
80	122	178	[a]31.0	28
80	121	178	[a]30.5	28
80	115	174	29.8	27
80	115	172	-----------	29
80	116	171	29.8	24
990	102	141	-----------	20
1,000	109	145	27.3	13
1,010	106	145	27.4	18
1,200	106	116	24.8	4
1,200	103	113	24.0	3
1,210	104	114	23.8	3
1,400	83.5	86.2	20.0	3
1,400	82.0	83.7	20.7	2
1,400	84.1	86.1	-----------	2

[a]Tuckerman gages with 10-inch specimens.

TABLE 3.- TENSILE PROPERTIES OF AGED INCONEL X SHEET - Continued

(b) 1,400° F for 4 hours (air cooled)

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Temperature, °F	Yield strength, ksi	Tensile strength, ksi	Young's modulus, psi	Elongation in 2 in., percent
80	113	171	[a]30.0×10^6	29
80	115	172	[a]29.8	30
80	113	171	[a]30.5	28
80	110	167	31.2	26
80	109	167	30.3	28
80	110	167	30.9	27
1,000	102	141	-----------	23
1,000	101	141	26.4	29
1,000	101	138	-----------	25
1,200	100	114	-----------	5
1,200	101	115	-----------	5
1,200	102	114	24.9	3
1,400	86.2	89.0	23.3	2
1,400	84.0	85.4	19.5	2
1,400	82.1	85.9	19.1	2

[a]Tuckerman gages with 10-inch specimens.

TABLE 3.- TENSILE PROPERTIES OF AGED INCONEL X SHEET - Concluded

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(c) 1,400° F for 1 hour (air cooled)

Temperature, $^{\circ}$F	Yield strength, ksi	Tensile strength, ksi	Young's modulus, psi	Elongation in 2 in., percent
80	107	166	[a]31.4×10^6	34
80	106	166	[a]30.8	35
80	107	166	(a)	32
80	106	164	29.5	33
80	108	167	29.7	31
80	-----	-----	[b]30.8	--
1,000	96.6	128	-----------	16
1,000	98.8	131	24.9	13
1,030	97.4	133	25.3	16
1,200	92.9	103	23.6	4
1,200	94.5	104	23.4	5
1,400	76.5	76.5	-----------	2
1,400	76.0	76.9	-----------	2

[a] 10-inch specimens.

[b] Tuckerman gages with 24-inch specimens.

TABLE 4.- TENSILE PROPERTIES OF INCONEL X SHEET IN

SOLUTION-ANNEALED AND AGED CONDITION

(a) 2,100° F for 1/2 hour (air cooled);
1,550° F for 24 hours (air cooled);
1,300° F for 20 hours (air cooled)

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Temperature, °F	Yield strength, ksi	Tensile strength, ksi	Young's modulus, psi	Elongation in 2 in., percent
80	98.0	160	[a]30.0×10^6	17
80	97.7	161	[a]30.5	17
80	97.7	161	[a]30.5	17
80	93.3	151	30.7	13
80	94.0	158	-----------	15
80	94.3	157	30.4	15
1,000	84.2	137	25.0	16
1,000	83.2	133	25.8	12
1,000	83.1	133	27.6	13
1,200	81.8	102	24.7	[b]2
1,200	81.5	105	25.0	[b]4
1,400	73.3	75.8	22.8	4
1,400	69.6	70.5	22.2	3

[a] Tuckerman gages with 10-inch specimens.

[b] Broke outside gage length.

TABLE 4.- TENSILE PROPERTIES OF INCONEL X SHEET IN

SOLUTION-ANNEALED AND AGED CONDITION - Continued

(b) 2,100° F for 2 hours (air cooled);
1,550° F for 24 hours (air cooled);
1,300° F for 20 hours (air cooled)

Temperature, °F	Yield strength, ksi	Tensile strength, ksi	Young's modulus, psi	Elongation in 2 in., percent
80	87.7	150	(a)	22
80	95.0	156	(a)	18
80	94.9	155	[a]28.9×10^6	21
80	94.5	162	29.7	23
80	91.3	157	30.1	21
1,000	83.3	123	27.1	11
1,000	85.2	127	26.7	11
1,000	80.6	126	25.4	12
1,200	80.6	91.5	23.0	3
1,200	81.2	97.6	23.9	4
1,400	68.8	70.0	-----------	3
1,400	67.6	68.2	23.0	3
1,400	67.5	68.6	19.0	2

[a] 10-inch specimens.

TABLE 4.- TENSILE PROPERTIES OF INCONEL X SHEET IN SOLUTION-ANNEALED AND AGED CONDITION - Concluded

(c) 2,100° F for 4 hours (air cooled);
1,550° F for 24 hours (air cooled);
1,300° F for 20 hours (air cooled)

Temperature, °F	Yield strength, ksi	Tensile strength, ksi	Young's modulus, psi	Elongation in 2 in., percent
80	87.4	141	[a]30.8×10^6	12
80	89.5	145	[a]30.5	13
80	88.7	-----	[a]31.0	14
80	88.4	146	30.6	14
80	88.8	139	-----------	11
80	88.5	152	31.8	18
1,000	80.6	127	25.3	11
1,000	79.6	121	24.7	11
1,000	80.2	126	24.6	12
1,200	77.2	100	22.7	4
1,200	78.0	102	23.9	4
1,400	66.9	68.5	21.0	7
1,400	70.2	72.6	22.5	4
1,400	70.0	73.2	23.2	6

[a]Tuckerman gages with 10-inch specimens.

TABLE 5.- TENSILE PROPERTIES OF INCONEL X SHEET

IN AS-RECEIVED CONDITION

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[Mill annealed]

Temperature, °F	Yield strength, ksi	Tensile strength, ksi	Young's modulus, psi	Elongation in 2 in., percent
80	46.5	112	(a)	57
80	49.3	112	(a)	57
80	47.2	110	[a]31.6×10^6	57
80	47.5	110	32.1	53
80	48.2	109	-----------	51
1,000	35.1	93.9	-----------	55
1,000	35.9	96.5	25.8	58
1,000	37.0	95.9	-----------	53
1,200	49.7	84.3	23.2	25
1,200	50.5	78.5	23.7	17
1,200	52.5	80.2	22.2	16
1,400	70.2	74.0	-----------	1
1,400	73.0	76.0	22.2	3
1,400	72.8	74.0	-----------	3

[a] 10-inch specimen.

TABLE 6.- CREEP AND STRESS-RUPTURE DATA FOR INCONEL X SHEET

Test temperature, °F	Stress, ksi	Minimum creep rate, hr^{-1}	Time, hr, for creep strain of -		Rupture life, hr
			0.1 percent	0.2 percent	
Heat treatment: 1,300° F - 20 hr					
1,000	110	4.0×10^{-5}	5.2	25.7	[a]162.5
	116	5.5×10^{-5}	.01	1.2	92.3
	120	1.9×10^{-4}	.01	.02	54.0
	129.1	2.2×10^{-4}	-----	-----	26.1
	137	----------	-----	-----	1.9
	137	----------	-----	-----	4.4
	142	----------	-----	-----	2.7
1,200	54	1.8×10^{-5}	-----	-----	177.0
	61	----------	-----	-----	91.1
	70	----------	-----	-----	36.7
	80	2.2×10^{-4}	2.0	7.0	16.6
	86	4.1×10^{-4}	.1	.3	8.3
1,400	26	2.0×10^{-5}	44.0	93.0	129.1
	30	----------	-----	-----	72.8
	36	1.5×10^{-4}	3.2	8.6	28.7
	42	1.4×10^{-4}	-----	-----	10.0
	47	9.0×10^{-4}	.5	1.7	4.8
Heat treatment: 1,400° F - 4 hr					
1,000	110	5.7×10^{-5}	0.1	0.5	89.2
	116	1.9×10^{-4}	-----	.2	42.1
	120	6.2×10^{-4}	.2	.3	20.3
	125	2.4×10^{-3}	.7	.2	8.3
	130	3.1×10^{-3}	.03	.1	3.8
1,200	60	----------	2.3	-----	126.5
	70	7.2×10^{-5}	6.2	10.5	44.1
	75	1.1×10^{-4}	3.3	12.3	31.5
	80	2.5×10^{-4}	.9	4.0	12.5
	84	----------	-----	-----	14.7
	84.3	2.6×10^{-4}	1.7	5.6	14.0
	90.0	8.6×10^{-4}	.4	1.5	8.5
1,400	30	----------	-----	-----	199.3
	35	----------	-----	-----	50.8
	40	----------	-----	-----	26.9
	45	----------	-----	-----	10.8
	48	----------	-----	-----	7.9
Heat treatment: 1,400° F - 1 hr					
1,000	102	1.7×10^{-5}	5.2	16.1	119.1
	107	1.3×10^{-4}	-----	-----	66.1
	110	1.5×10^{-4}	1.6	4.9	75.7
	111	2.1×10^{-4}	.4	.9	29.1
	114	----------	-----	-----	16.3
	117	1.8×10^{-3}	5.3	-----	12.1
	120	3.9×10^{-3}	.08	.2	5.0

[a]No failure.

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TABLE 6.- CREEP AND STRESS-RUPTURE DATA FOR INCONEL X SHEET - Concluded

Test temperature, °F	Stress, ksi	Minimum creep rate, hr^{-1}	Time, hr, for creep strain of - 0.1 percent	Time, hr, for creep strain of - 0.2 percent	Rupture life, hr
Heat treatment: 1,400° F - 1 hr - Continued					
1,200	56	----------	----	----	137.7
	60	3.2×10^{-5}	8.6	39.5	67.9
	66	----------	----	----	29.5
	70.8	8.5×10^{-5}	6.2	----	14.1
	76	2.2×10^{-4}	1.2	5.2	11.4
	76	----------	----	----	11.6
	80	----------	----	----	6.9
1,400	30	----------	----	----	142.4
	30	9.1×10^{-5}	.8	2.6	100.5
	35	9.6×10^{-5}	----	----	47.9
	35	----------	5.3	15.2	53.8
	40	3.3×10^{-4}	.8	3.3	20.3
	43	4.8×10^{-4}	.5	2.0	14.2
	47	----------	----	----	8.0
Heat treatment: 2,100° F - 1/2 hr; 1,550° F - 24 hr; 1,300° F - 20 hr					
1,200	72	----------	3.5	18.0	189.5
	75	2.8×10^{-5}	7.8	74.0	85.0
	80	4.3×10^{-5}	----	----	36.3
	88	8.4×10^{-5}	.4	1.3	14.0
Heat treatment: 2,100° F - 2 hr; 1,550° F - 24 hr; 1,300° F - 20 hr					
1,000	97	1.4×10^{-5}	4.0	0.2	326.7
	103	1.4×10^{-5}	.03	.1	45.1
	110	5.8×10^{-4}	.02	.1	12.7
	115	7.7×10^{-3}	----	.1	7.3
1,200	65	----------	----	----	108.4
	71	3.5×10^{-5}	9.8	33.6	65.7
	77	2.4×10^{-4}	1.1	3.7	22.9
	80	----------	----	----	7.0
1,400	32	7.8×10^{-5}	3.1	10.3	92.0
	35	8.5×10^{-5}	4.0	16.0	53.4
	43	4.3×10^{-4}	.6	2.4	11.7
	49	2.8×10^{-3}	.2	.7	3.1
Heat treatment: 2,100° F - 4 hr; 1,550° F - 24 hr; 1,300° F - 20 hr					
1,200	72	6.5×10^{-5}	4.0	13.0	61.0
	75	1.5×10^{-4}	3.4	8.8	63.3
	85	2.2×10^{-3}	----	.2	3.7

TABLE 7.- CREEP AND STRESS-RUPTURE STRENGTH

OF INCONEL X SHEET

Test temperature, °F	Creep strength for 0.2-percent creep strain, ksi, in -		Stress rupture strength, ksi, in -	
	5 hr	10 hr	10 hr	100 hr
Heat treatment: 1,300° F - 20 hr				
1,000	114	112	137	116
1,200	82	80	86	58
1,400	41	37	42	27
Heat treatment: 1,400° F - 4 hr				
1,000	---	---	124	109
1,200	82	78	98	62
1,400	---	---	45	31
Heat treatment: 1,400° F - 1 hr				
1,000	108	104	117	104
1,200	76	70	75	57
1,400	39	36	45	41
Heat treatment: 2,100° F - 1/2 hr; 1,550° F - 24 hr; 1,300° F - 20 hr				
1,000	---	---	---	---
1,200	82	79	92	74
1,400	---	---	---	---
Heat treatment: 2,100° F - 2 hr; 1,550° F - 24 hr; 1,300° F - 20 hr				
1,000	100	98	112	100
1,200	76	74	79	70
1,400	38	34	44	31
Heat treatment: 2,100° F - 4 hr; 1,550° F - 24 hr; 1,300° F - 20 hr				
1,000	---	---	---	---
1,200	77	75	82	68
1,400	---	---	---	---

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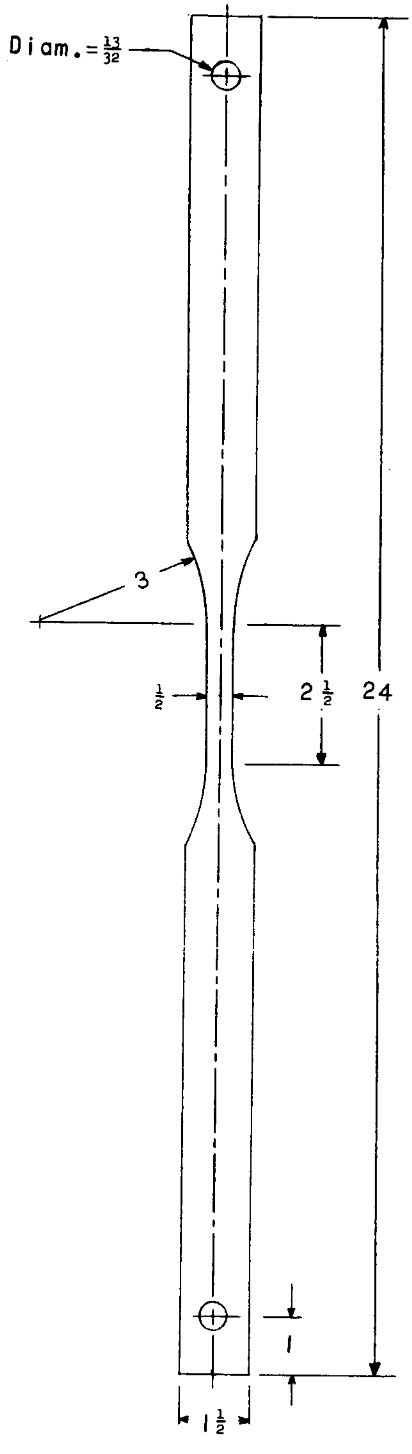

Figure 1.- Tensile and creep specimen. All dimensions are in inches.

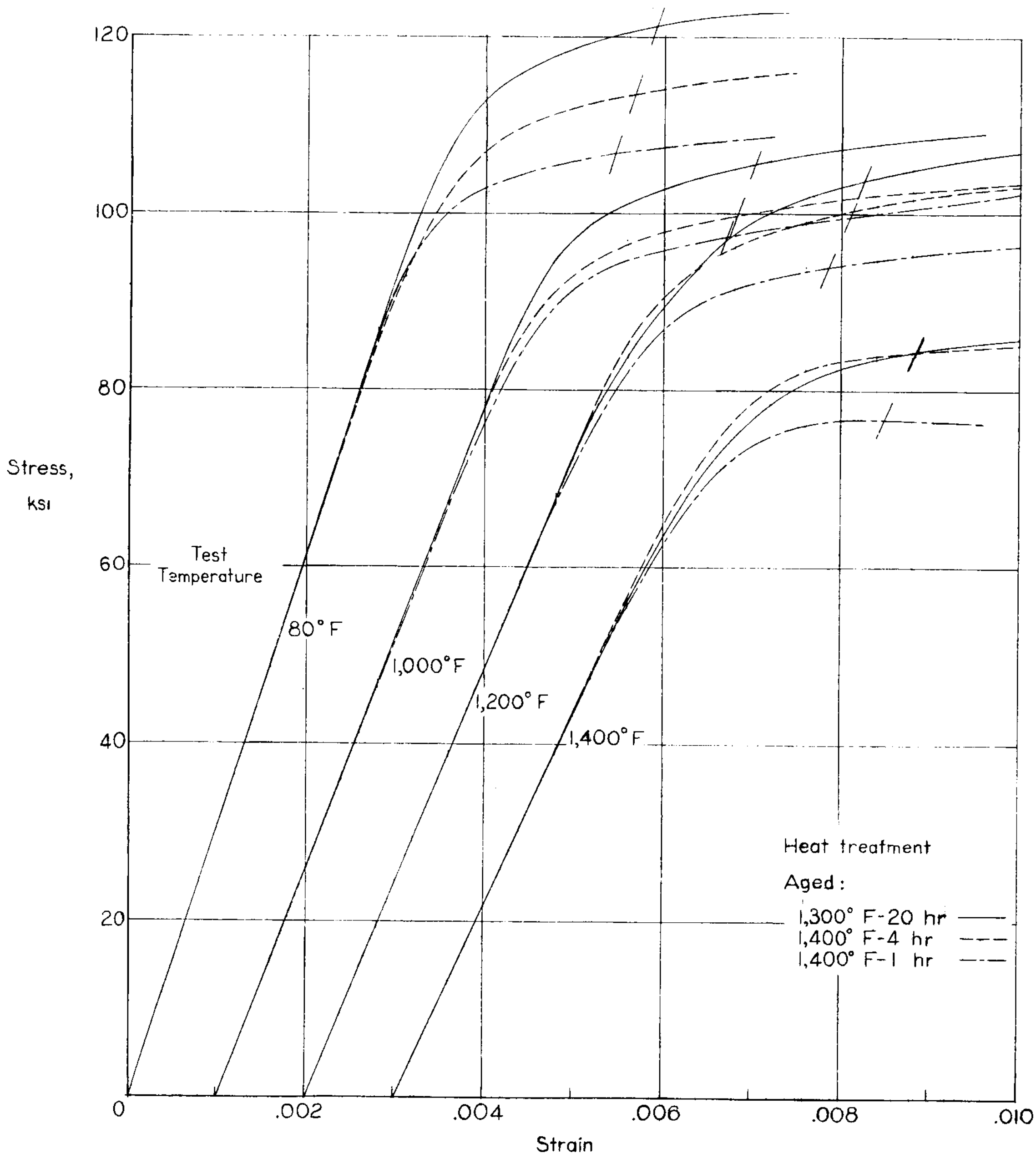

Figure 2.- Elevated-temperature tensile stress-strain curves for Inconel X sheet for three aged conditions. Strain rate 0.002 inch per minute. Tick marks on each curve indicate 0.2-percent-offset yield strength.

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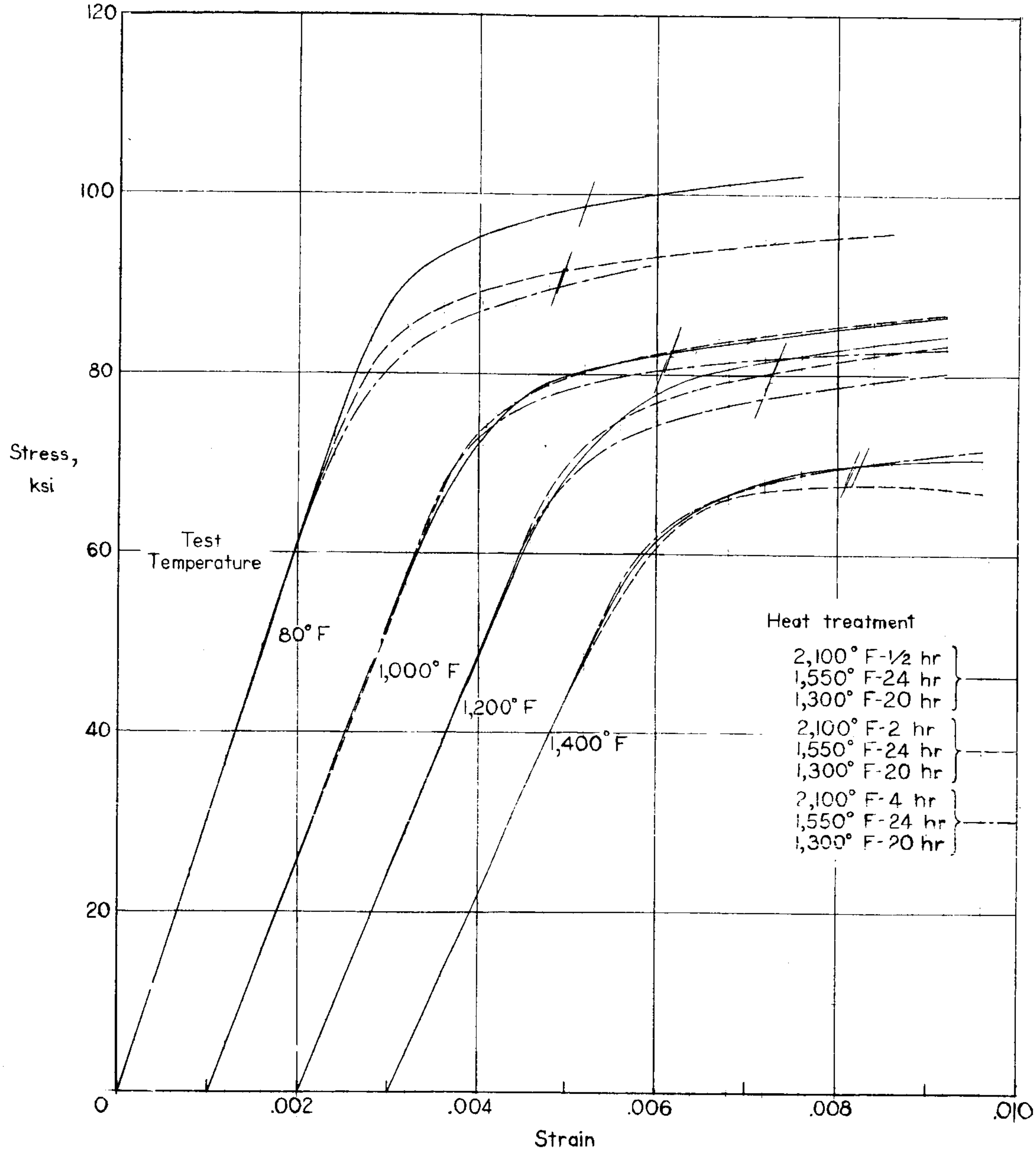
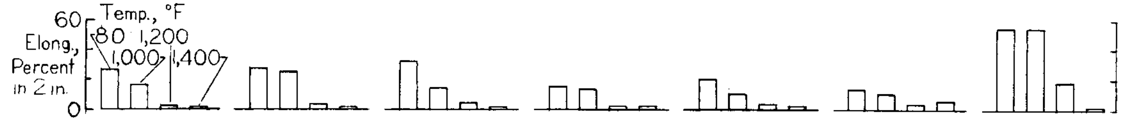
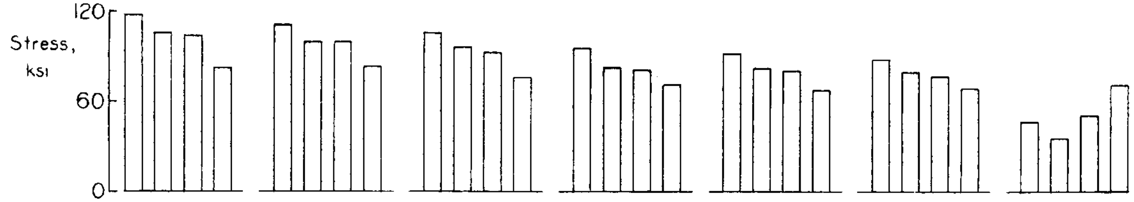


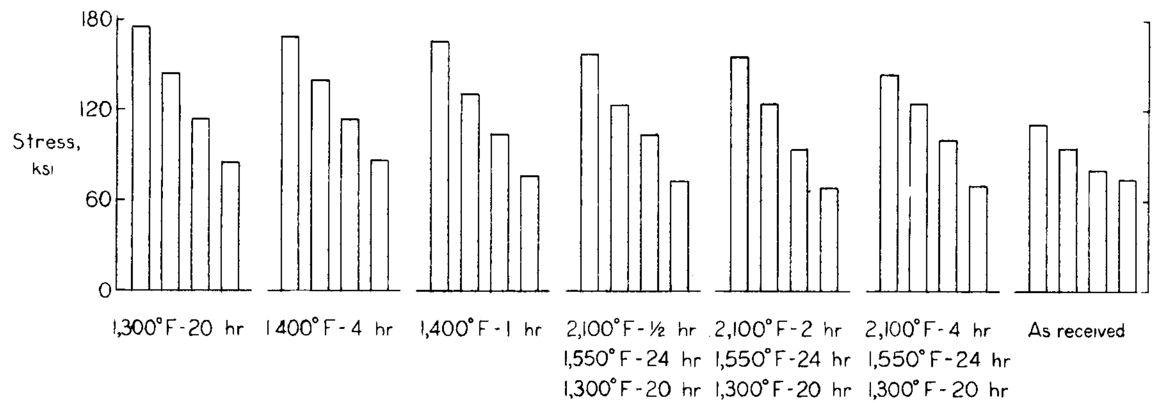
Figure 3.- Elevated-temperature tensile stress-strain curves for Inconel X sheet for three solution-annealed and aged conditions. Strain rate 0.002 inch per minute. Tick marks on each curve indicate 0.2-percent-offset yield strength.



(a) Elongation.

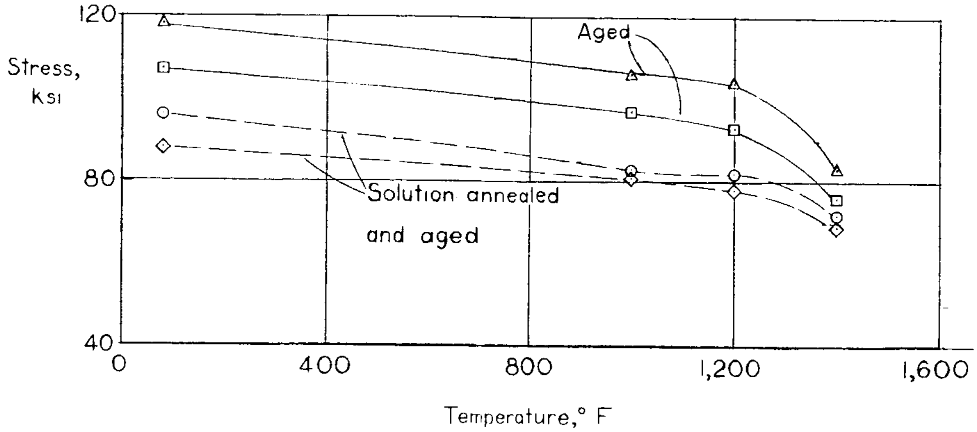


(b) Yield strength.

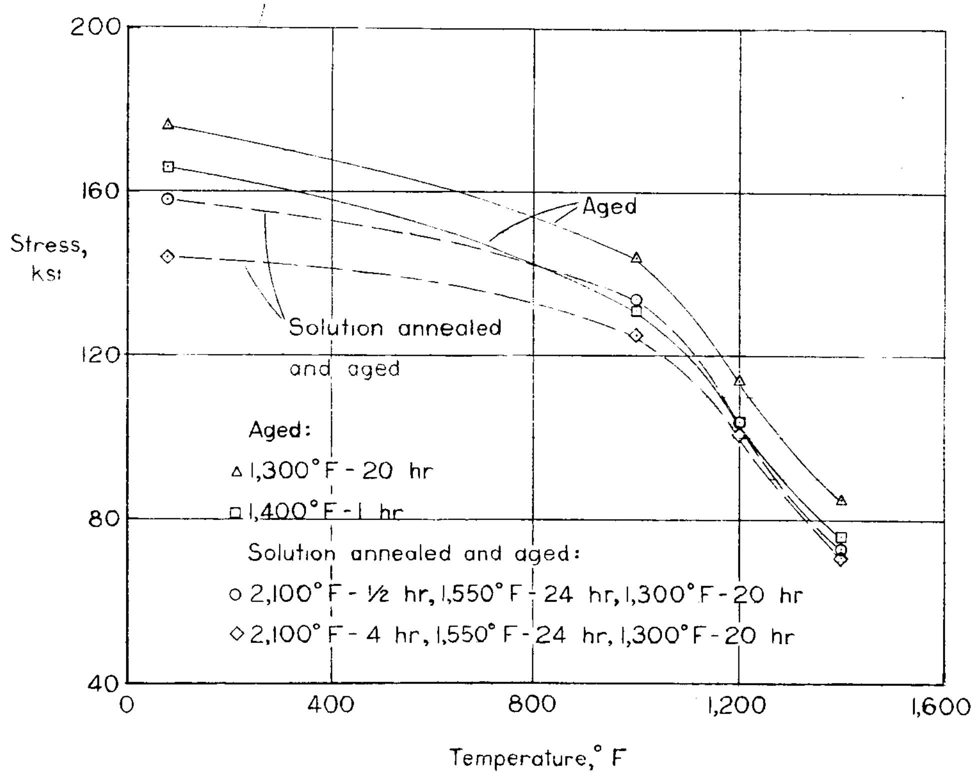


(c) Tensile strength.

Figure 4.- Comparison of tensile properties of Inconel X sheet at 80°, 1,000°, 1,200°, and 1,400° F for six different heat treatments and as-received condition.



(a) Yield strength.



(b) Tensile strength.

Figure 5.- Tensile properties of aged, and solution-annealed and aged Inconel X sheet from room temperature to 1,400° F.

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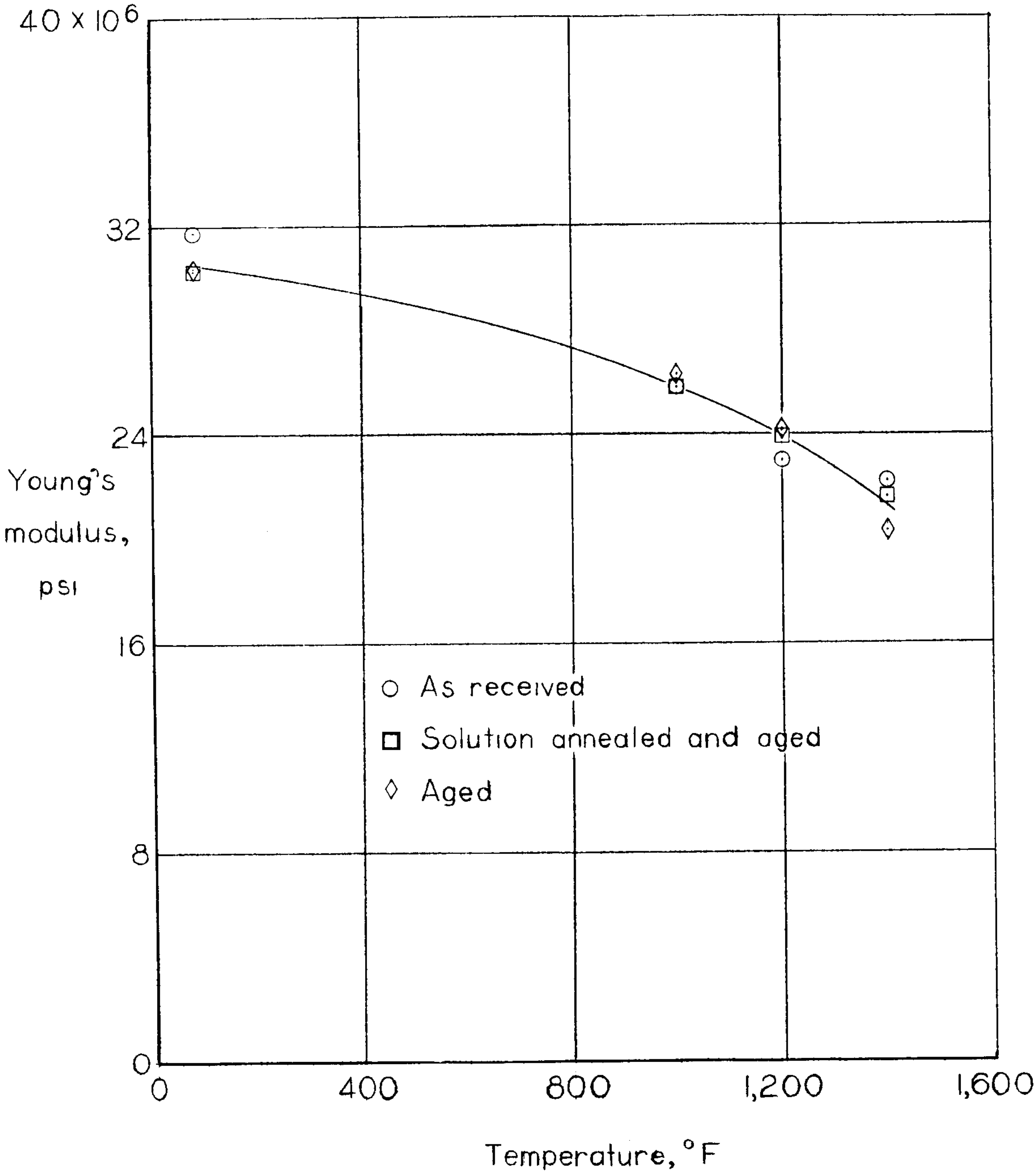

Figure 6.- Variation of Young's modulus with temperature for as-received and two heat-treated conditions for Inconel X sheet.

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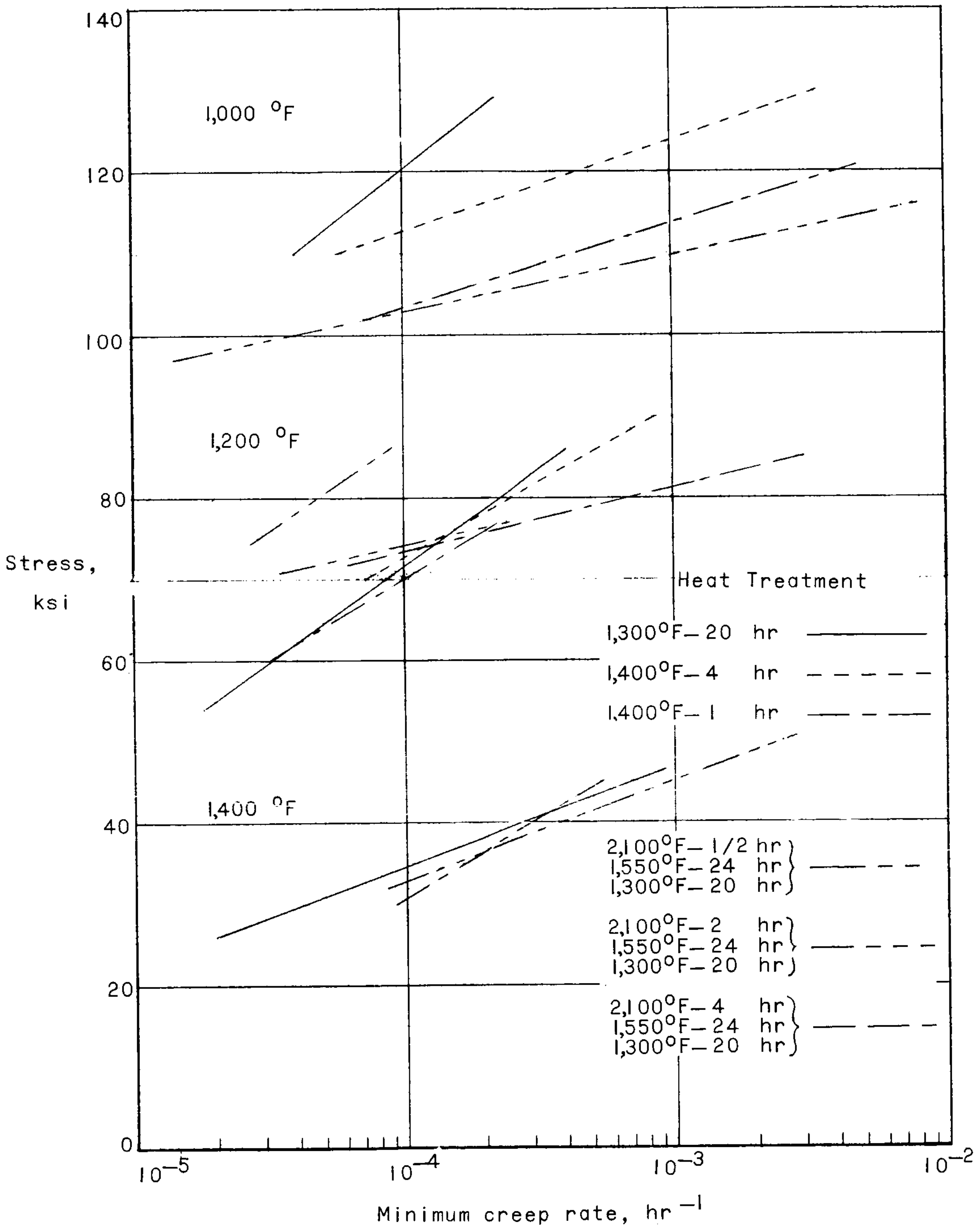
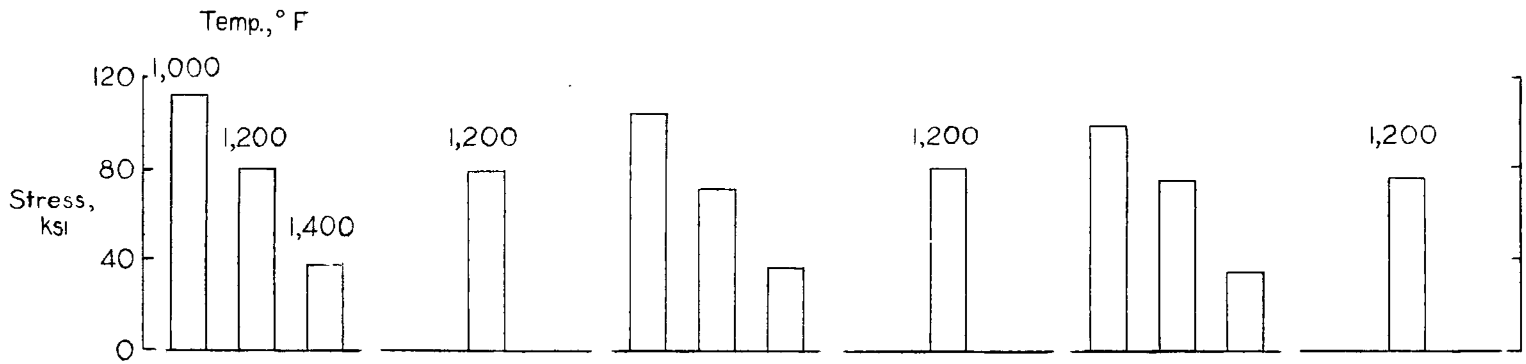
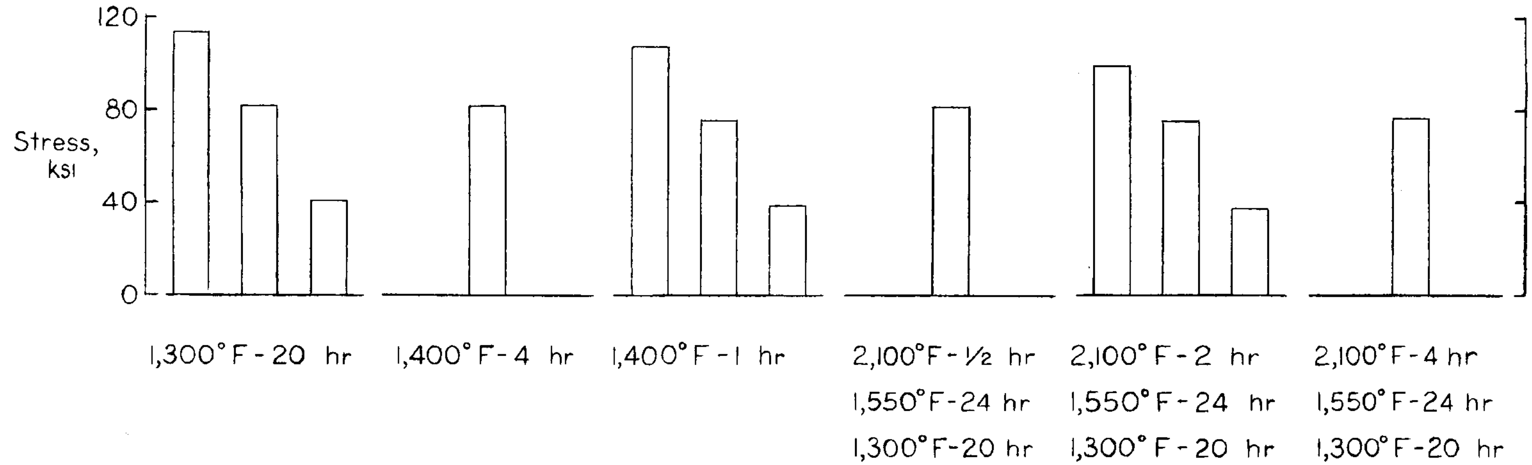


Figure 7.- Minimum creep rate for Inconel X sheet at 1,000°, 1,200°, and 1,400° F for three solution-annealed and three aged heat treatments.

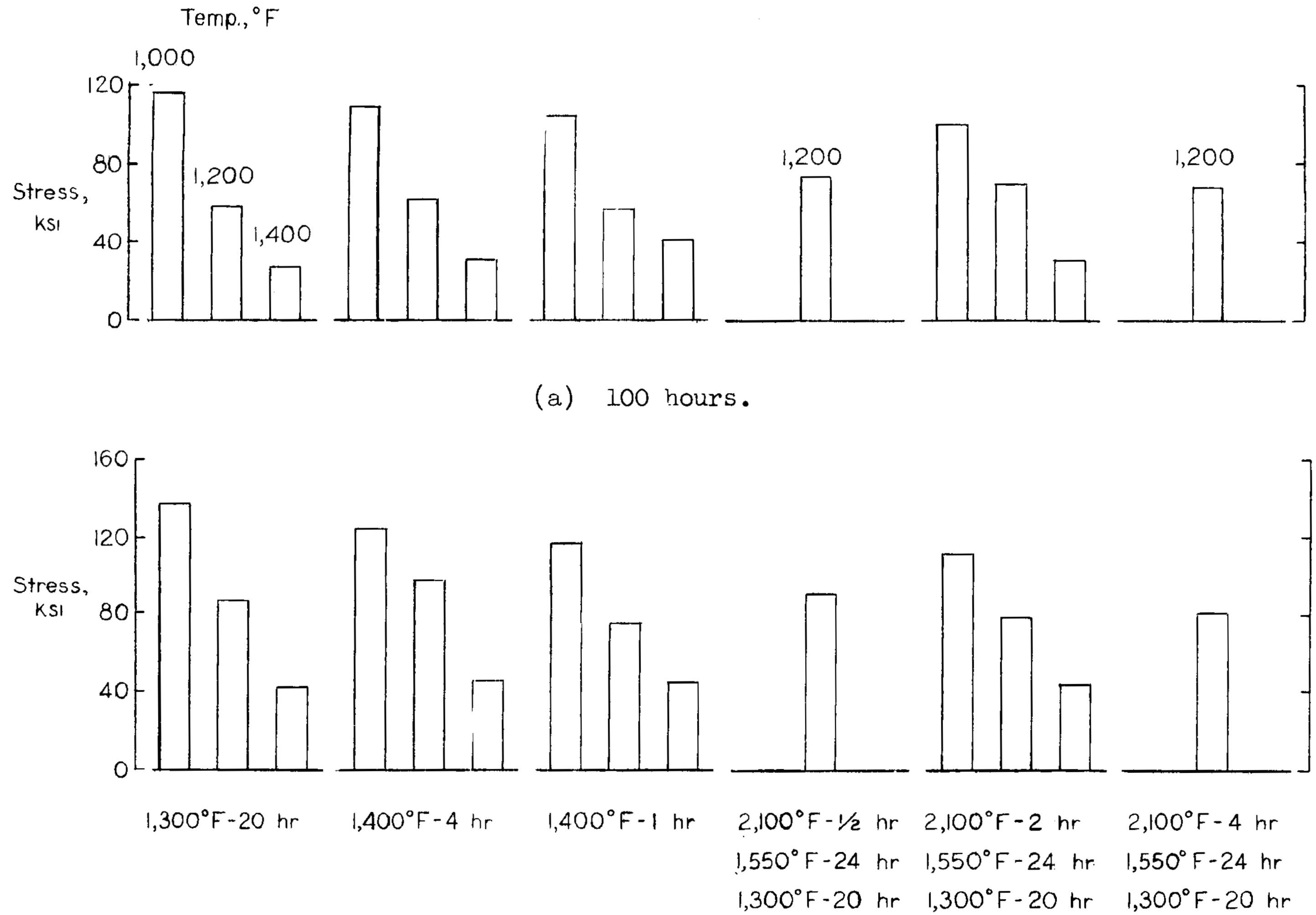


(a) 0.2-percent creep strain in 10 hours.



(b) 0.2-percent creep strain in 5 hours.

Figure 8.- Comparison of creep strength for 0.2-percent creep strain for 5 and 10 hours for Inconel X sheet at 1,000°, 1,200°, and 1,400° F for six different heat treatments.



(a) 100 hours.

(b) 10 hours.

Figure 9.- Comparison of stress-rupture strength for 10 and 100 hours for Inconel X sheet at 1,000°, 1,200°, and 1,400° F for six different heat treatments.

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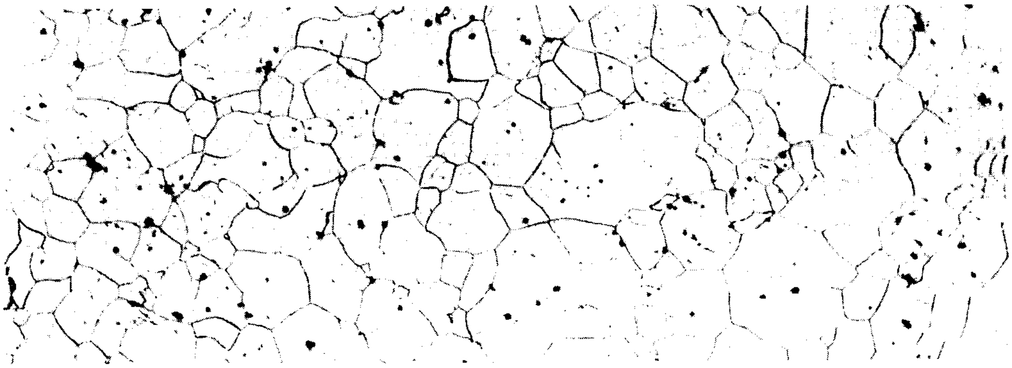
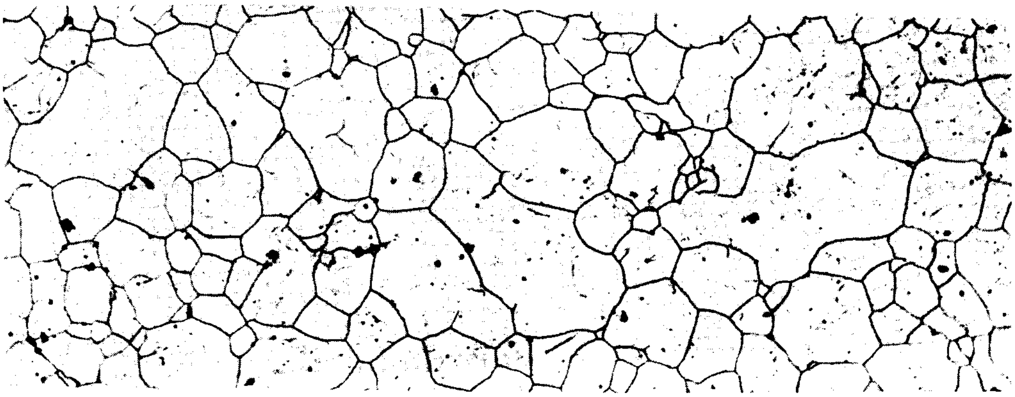
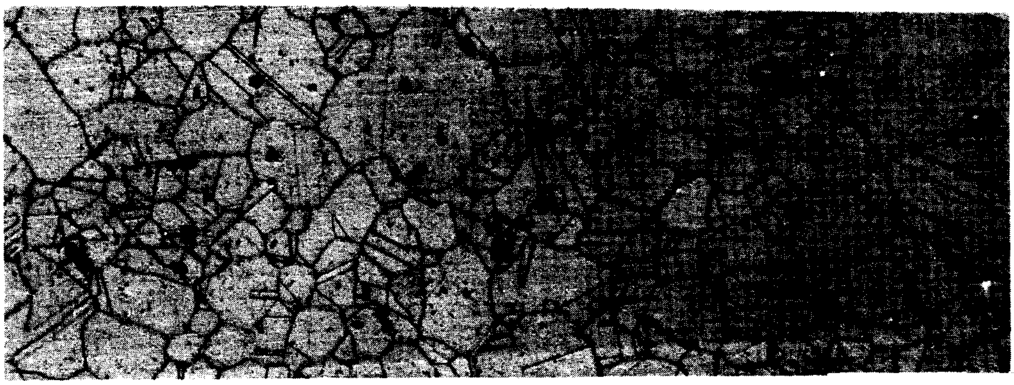


Solution annealed 1/2 hour and aged.



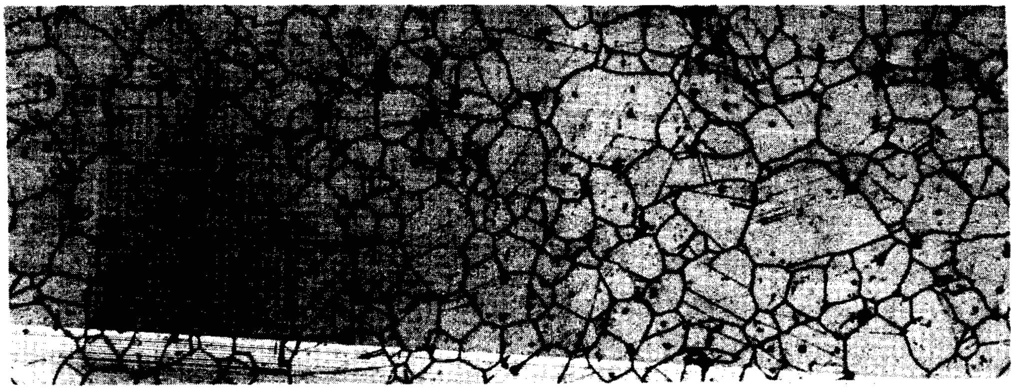
Solution annealed 2 hours and aged.



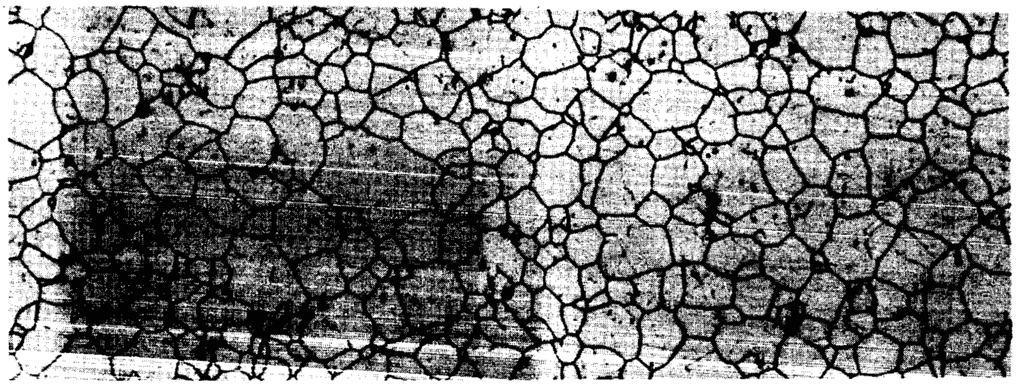
Solution annealed 4 hours and aged.

(a) Solution annealed and aged. L-60-225

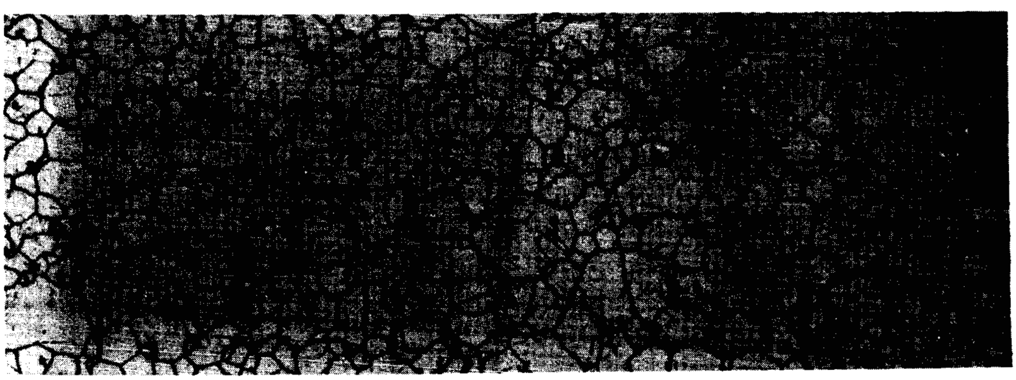
Figure 10.- Microstructures for Inconel X sheet. X 100.



Aged 1,300 for 20 hours.



Aged 1,400 for 1 hour.



Aged 1,400 for 4 hours.

(b) Aged. L-60-226

Figure 10.- Continued.

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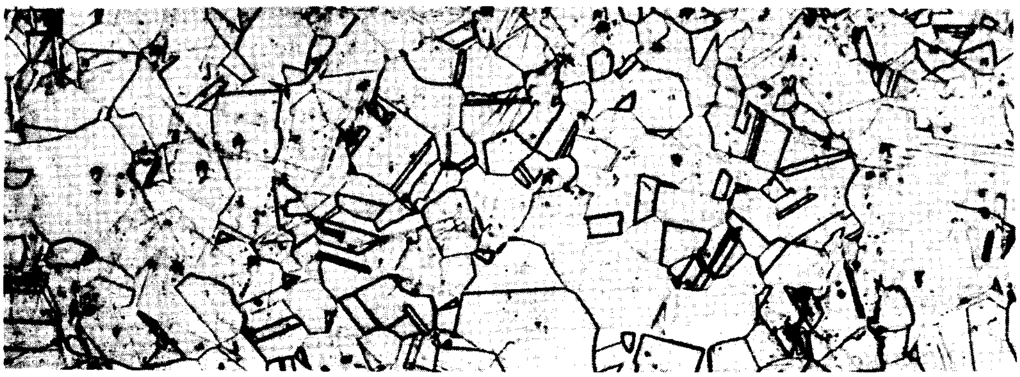

(c) As received. L-60-227

Figure 10.- Concluded.